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STRESS AND FATIGUE LIFE MODELING OF CANNON BREECH CLOSURES INCLUDING EFFECTS OF MATERIAL STRENGTH AND RESIDUAL STRESS

JOHN H. UNDERWOOD
MICHAEL J. GLENNON

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US ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT LABORATORIES
WATERVLIET, N.Y. 12189-4050

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13. ABSTRACT (Maximum 200 words)

Laboratory fatigue life results are summarized from several test series of high-strength steel cannon breech closure assemblies pressurized by rapid application of hydraulic oil. The tests were performed to determine safe fatigue lives of high-pressure components at the breech end of the cannon and breech assembly. Careful reanalysis of the fatigue life tests provides data for stress and fatigue life models of breech components, over the following ranges of key parameters: 380 to 745 MPa cyclic internal pressure; 100 to 160-mm bore diameter cannon pressure vessels; 1040 to 1170 MPa yield strength A723 steel; no residual stress; shot-peen residual stress; overload residual stress.

Modeling of applied and residual stresses at the location of the fatigue failure site is performed by elastic-plastic finite element analysis using ABAQUS and by solid mechanics analysis. Shot-peen and overload residual stresses are modeled by superposing typical or calculated residual stress distributions on the applied stresses. Overload residual stresses are obtained directly from the finite element model of the breech, with the breech overload applied to the model in the same way as with actual components. Modeling of the fatigue life of the components is based on the fatigue intensity factor concept of Underwood and Parker, a fracture mechanics description of life that accounts for residual stresses, material yield strength, and initial defect size.

The fatigue life model includes six test conditions in a stress versus life plot with an R^2 correlation of 0.94. The model shows significantly lower correlation when known variations in yield strength, stress concentration factor, or residual stress are not included in the model input, thus demonstrating the model sensitivity to these variables.

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INTRODUCTION

Full-scale fatigue life tests of cannon breech assemblies are routinely conducted as a laboratory simulation of firing conditions in order to directly determine the safe fatigue life of the more critical cannon breech components. These tests are an ideal source of information for development of a cannon breech fatigue life model, which is the objective of this work. By carefully re-examining the results of cannon breech fatigue life tests and performing some additional finite element and solid mechanics analyses of the tests, a cannon breech fatigue life model has been developed that may have general utility for cannon development. The approach used in the work is similar to that of Underwood and Parker (ref 1), where cannon tube fatigue life tests were used to develop a fatigue life model for the pressurized, thick-wall breech end of cannon tubes with various material, configuration, and loading conditions. This earlier work introduced the fatigue intensity factor concept, a fracture mechanics description of fatigue life that accounts for residual as well as applied local stresses, and also accounts for effects on life due to variations in material yield strength and initial defect size.

Figure 1 shows two types of breech assemblies that are used with modern cannon, the single-lug and the multi-lug slide-block breech. These two types are those used in most recent cannon breech fatigue life testing, and are the types considered in the development of the breech fatigue life model discussed here. Figure 1 shows the basis of the fatigue life model. The pressure applied to the breech block over an area of diameter, d, combined with the dimensions shown in the sketches, provides a measure of nominal stress in the two "arms" of the breech. Then, using the usual elastic stress concentration factor for the lug root (the observed location of cracking) and the value of any residual stress at the lug root, the total local stress at the lug root is described. This local stress, combined with the yield strength of the steel used for the breech, is the basis for the fatigue life model. In the following sections, the analysis used to develop the model will be described, and the log-log plots of stress range versus life that come from the analysis will be presented, to demonstrate the characteristics of the model.
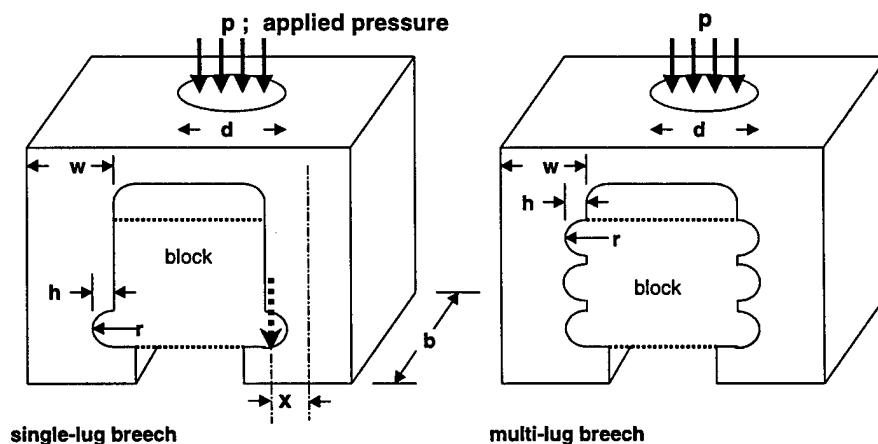

Figure 1. Typical single-lug and multi-lug cannon breech configurations.

ANALYSIS

An expression for the total nominal tensile stress on the inner surface of the breech adjacent to the lug root can be written as the sum of the uniaxial tensile and outer fiber bending stresses produced by the pressure applied to the breech block. In equation (1) the first term is the uniform tensile stress carried by one-half of the breech, and the second term is the outer fiber bending stress corresponding to a moment characterized by position, x, and force, $[p\pi d^2/8]$

$$S_{NOMINAL} = p\pi d^2/8wb + 6x[p\pi d^2/8]/bw^2 \qquad (1)$$

where

p is the pressure applied to the block.
d is the diameter of the area of pressure application.
b and w are the depth and width of the breech half.
x is the moment arm of the force applied to the breech half.

The nominal stress in the area of the lug, from equation (1), can be used to write an expression for the *local* stress tangent to the lug root surface, which should provide a description of fatigue cracking local to the lug root. The local stress is the sum of applied stress, S_A, at the lug root due to the applied pressure, and residual stress, S_R, the persistent stress at the lug root surface produced by manufacturing processes.

$$S_{LOCAL} = S_A + S_R \qquad (2)$$

The range of local applied stress at the notch root, ΔS_A, the stress of prime importance in controlling fatigue, can be written as the product of nominal stress from equation (1), and the elastic stress concentration factor of the lug root, k, as follows:

$$\Delta S_A = k \left[\Delta p\pi d^2/8wb\right] \left[1 + 6x/w\right] \qquad (3)$$

The stress concentration factor for a notch of depth h and root radius r (for $h/r > 0.5$) in a rectangular section of width w is available from Roark and Young (ref 2), and is repeated here as follows:

$$k = k_1 + k_2(h/w) + k_3(h/w)^2 + k_4(h/w)^3$$

$$k_1 = 0.721 + 2.394(h/r)^{1/2} - 0.127(h/r)$$

$$k_2 = 1.978 - 11.489(h/r)^{1/2} + 2.211(h/r)$$

$$k_3 = -4.413 + 18.751(h/r)^{1/2} - 4.596(h/r)$$

$$k_4 = 2.714 - 9.655(h/r)^{1/2} + 2.512(h/r) \qquad (4)$$

Note that one of the test series has an h/r ratio less than 0.5, but having one consistent calculation of k for all cases outweighs any problem this may cause.

Finally, the fatigue intensity factor (FIF) is calculated as

$$FIF = \Delta S_{LOCAL} \quad a_i^{1/6} \quad S_{Y-AVE}/S_Y \qquad (5)$$

where a_i is the initial defect size and S_{Y-AVE} and S_Y are the mean yield strength for all tests and the individual yield strength for a given test component, respectively. Reference 1 contains additional information on FIF.

Equations (1) through (5) were used as the basis for the cannon breech fatigue life model. The one variable in the equations that could not be directly determined from the input information was the bending moment arm, x. Its value was determined to be $0.45w$, by setting the value of the local applied stress range at the notch root, ΔS_A in equation (3), equal to the stress obtained from finite element analysis, for the same notch root radius location and the same load applied to the finite element calculations as that applied to the breech model. This value of $x/w = 0.45$ was used for all model calculations, even though it was based on finite element analysis of just some of the model configurations.

The finite element analysis used was a two-dimensional model of a portion of the breech arm and breech block using ABAQUS. Figure 2 shows the configuration of the model and representative results, which are contours of maximum principal stress from the calculations. The lug root on the left had the highest values of principal stress (tangent to the lug root surface), and was also the location of fatigue failure in the tests. This value of tangential lug root stress from finite element analysis was the value used to determine the $x/w = 0.45$ using equation (3). Upcoming results will compare values of the local applied stress range from the model (equation (3)) with values from the finite element calculations.
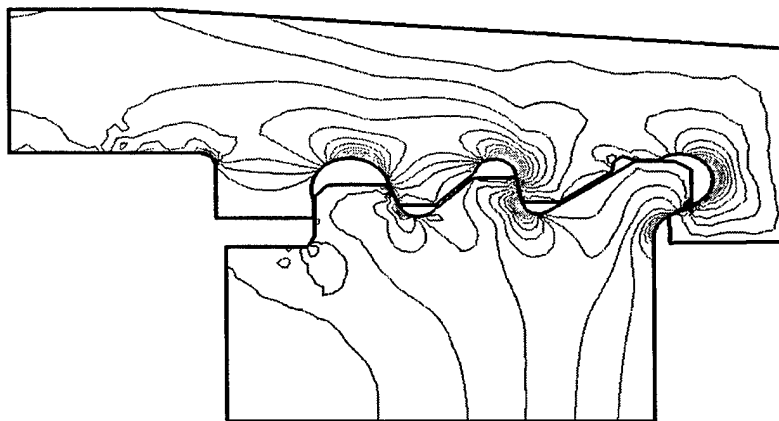

Figure 2. Finite element contours of maximum principal stress in series 1 multi-lug breech with typical firing load applied; following overload to produce residual stresses at lug root radii.

One further comment on the results from analysis should be made. Careful study of the maximum principal stress contours at and near the lug root surface reveals that the highest value of maximum principal stress is at a location 2-mm below the lug root surface. This cannot be seen clearly in Figure 2, but it is verified from the finite element data. The reason for the highest values occurring below the surface is the overload to which the finite element model (and the actual component) has been subjected. The overload causes tangential tensile yielding during the overload and tangential compressive residual stress at the lug root surface after release of the overload. The compressive residual stress at the surface shifts the highest value of maximum principal stress to a location slightly below the surface. These effects of tensile overload on a notched steel component are well known. Underwood (ref 3) has described prior experimental work with a notch configuration and type of steel similar to those here.

FATIGUE LIFE TESTS

A summary of the breech fatigue life tests considered here is given in Table 1. The twenty-eight tests of series 1, 4, 5, and 6 were used to develop the breech fatigue life model, and the results of the two tests of series 2 and 3 were compared with the model predictions. Note that series 1 and 5 have two sub-series each; two types of residual stress in series 1 and two values of pressure in series 5. These differences make, in effect, six modeling conditions in the twenty-eight tests of series 1, 4, 5, and 6 that can be used to develop the model. Values of 0.2 percent offset yield strength of the ASTM A723 pressure vessel steel used for each of the test series are listed in Table 1. Values of test pressure and of the pertinent dimensions are also listed.

Table 1. Summary of Breech Configurations and Test Conditions

Test Series	Number of Tests	Lug Type	Yield Stress (S_Y) MPa	Test Pressure (p) MPa	Load Diameter (d) mm	Arm Width (w) mm	Arm Depth (b) mm	Root Radius (r) mm	Root Depth (h) mm	Residual Stress
1	11	Multi	1130	573	136	81	373	11	22	* Overload **Shot-peen
2	1	Multi	1080	745	162	127	437	20	30	Overload
3	1	Multi	1170	406	184	125	448	20	33	Shot-peen
4	6	Single	1110	669	158	125	427	17	8	None
5	5	Single	1040	380* 414**	111	56	312	7	2	None
6	6	Single	1170	573	136	92	368	11	11	None

Figure 3 shows a log-log plot of the fatigue life test results using FIF in place of stress range, so that variations in initial crack size and yield strength can be incorporated as necessary. There were no known differences in material or manufacturing process that would have affected initial crack size in the breech tests, so the same value of initial crack size was used in all cases here, that is, $a_i = 0.01$-mm. However, the variation in yield strength shown in Table 1 was incorporated in the plot of Figure 3. Considering the significant differences in material and configuration among the fatigue life tests, the R^2 correlation of 0.94 is considered to be very good. The description of the inputs to the breech fatigue life model and the model results are discussed next.
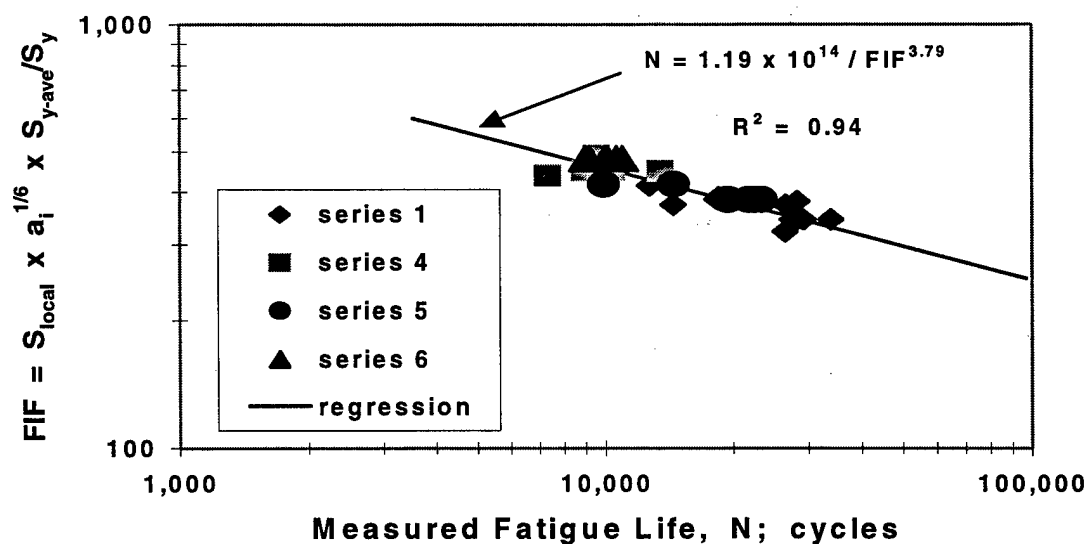
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The plot shows:

$$N = 1.19 \times 10^{14} / FIF^{3.79}$$

$$R^2 = 0.94$$

Y-axis: $FIF = S_{local} \times a_i^{1/6} \times S_{y\text{-}ave}/S_y$ (from 100 to 1,000)

X-axis: Measured Fatigue Life, N; cycles (from 1,000 to 100,000)

Legend:
- series 1
- series 4
- series 5
- series 6
- regression

Figure 3. Measured fatigue lives from four series of cannon breech tests.

BREECH FATIGUE LIFE MODEL

The key input parameters to the model and some results are listed in Table 2. The important ratio of lug root residual stress to yield strength, S_R/S_Y, was determined directly or indirectly from the finite element results. The two values of overload residual stress relative to yield strength in Table 2, 0.29 and 0.34, are directly from finite element results. However, the 0.21 value used for shot-peen residual stress was arbitrarily selected to obtain the same ratio of shot-peen to overload life in the model as that observed from the tests, that is, a ratio of 0.64 for test series 1. This test series was purposely expanded to eleven tests in order to accurately determine this shot-peen to overload life ratio, because it is typically difficult to determine the exact values and depths of shot-peen residual stresses in test components. Next listed in Table 2 are the values of stress concentration factor determined from equation (4) for the various series. Next is the comparison of local applied stress at the lug root, discussed earlier. The essentially identical values of ΔS_A for the model and for the series 1 finite element results were the basis for selecting $x/w = 0.45$, which was used for all model calculations as has been discussed. Note that this gives quite similar values of ΔS_A for series 2 and 3 as well. Finally, the mean measured lives are compared with the model lives in Table 2 and in Figure 4.

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Table 2. Summary of Model Input and Results

Test Series	Residual Stress	S_R/S_Y	Stress Concentration (k)	Applied Stress Range at Lug		Breech Fatigue Life	
				$\Delta S_{A\text{-}FEA}$ MPa	$\Delta S_{A\text{-}MODEL}$ MPa	N_{TEST} Cycles	N_{MODEL} Cycles
1	Overload	0.29	2.04	1040	1030	28,601	28,900
	Shot-peen	0.21				18,446	18,600
2	Overload	0.34	1.96	1070	1000	21,875	35,200
3	Shot-peen	0.21	1.91	710	690	49,928*	198,000
4	None	--	2.05	--	920	9,803	10,100
5	None	--	1.84	--	720	21,774	19,200
					780	12,200	13,900
6	None	--	2.25	--	1020	9,971	8,200

* No failure, test interrupted.

Six mean values (from the twenty-eight individual test results in Figure 3) are shown in Figure 4 along with the same regression line shown earlier. The utility of this type of model plot is that it provides a useful comparison for subsequent less well-established tests, such as the two single tests of series 2 and 3. Each of these single tests was in need of other results for comparison—test 2 because the fatigue failure occurred at a material defect located well removed from the usual breech failure location, and test 3 because the testing was interrupted due to limited patience and resources on the part of those conducting the test. Each of these tests, when considered in relationship to the model results in Table 2 and Figure 4, was clearly not at the end of its expected life. So the model helps gain understanding of these two single-test results.
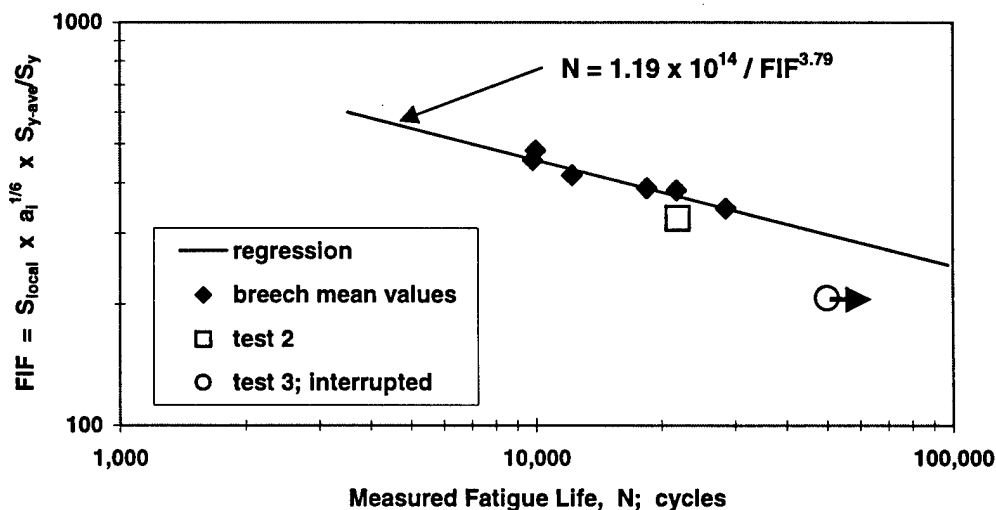

Figure 4. Comparison of two recent tests with mean lives from cannon breech tests.

A measure of the change to be expected from the model as a result of changes in certain key variables can be seen in the results of Table 3. The R^2 correlation coefficient mentioned earlier, 0.94, is compared with the R^2 value that results when the known variation in a given variable is intentionally deleted from the model. First, rather than using the values of yield strength from Table 1, a constant value of 1100 MPa is used in the calculation of FIF for the model, resulting in an R^2 of 0.74. Similarly, removing the variation of residual stress or stress concentration factor results in significant reduction in correlation. Thus, each of these three model variables, S_Y, S_R, and k, is shown to have a significant effect on the model results.

Table 3. Variation of Model Results with Three Variables

	Yield Strength Input to Model	Residual Stress Input to Model	Stress Concentration Input to Model	Correlation Coefficient R^2
Standard Model	Individual S_Y Values	$S_R/S_Y = -0.21$; Peen $S_R/S_Y = -0.29$; Overload	Individual k Values	0.94
No S_Y Variation	$S_Y = 1100$ MPa	$S_R/S_Y = -0.21$; Peen $S_R/S_Y = -0.29$; Overload	Individual k Values	0.74
No S_R Variation	Individual S_Y Values	$S_R/S_Y = -0.25$	Individual k Values	0.83
No k Variation	Individual S_Y Values	$S_R/S_Y = -0.21$; Peen $S_R/S_Y = -0.29$; Overload	$k = 2.05$	0.71

Next, it may be instructive to compare the cannon breech fatigue life model results discussed here with the cannon tube fatigue life model from earlier work (ref 1). The comparison in Figure 5 shows lower correlation for the tube results, but a review of that work reveals that a broader range of configurations and more variation in pretest material condition were included in the twelve groups of tube tests, compared with the six groups of breech tests here. More disconcerting are the much smaller values of FIF for tube results, compared with breech results at similar values of fatigue life. A likely reason for this difference in FIF values is inaccurate determination of the autofrettage residual stresses in the tube results. Recent work by Parker and coworkers (ref 4) has shown that the Bauschinger corrections for residual stresses in thick-wall tubes are much more significant than had been realized. The most significant corrections are at the tube inner radius, the location that often has most control over tube fatigue life. Once the proper Bauschinger effect has been included in the residual stress contribution to FIF in the description of tube fatigue life, it is hoped that tube and breech fatigue life models will be more closely aligned.
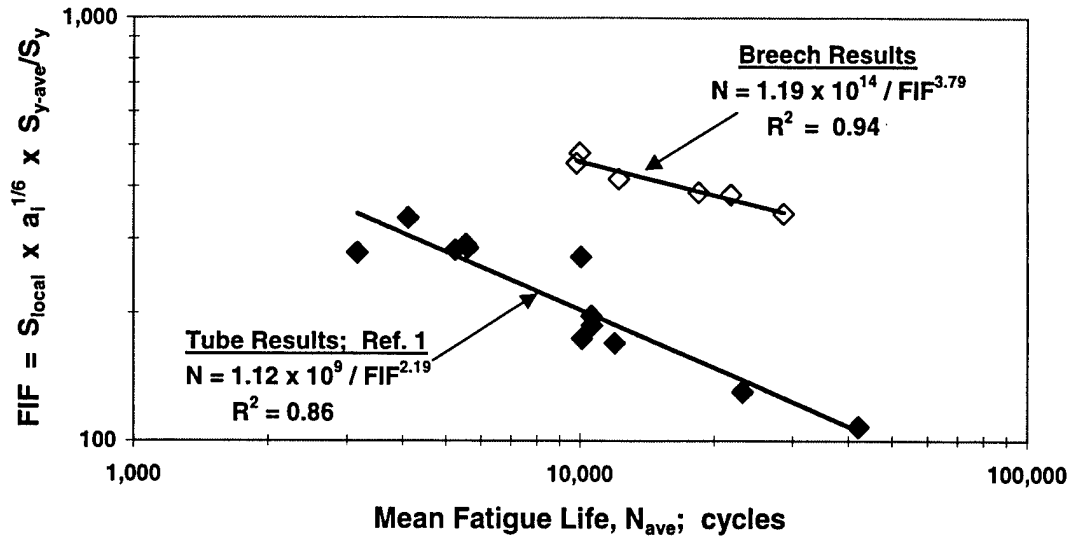
Figure 5. Comparison of cannon breech and cannon tube fatigue results.

A final demonstration of the breech fatigue life model resulted in a comparison of calculated lives from the model for the two test series, including various levels of applied and residual stresses. This comparison is shown in Figure 6. Calculated lives for the normal applied pressure and for 5, 10, 15, and 20 percent above normal pressure are shown for the series 1 and 5 conditions. The significant reductions in life due to a reduced level of compressive residual stress, for series 1, and for a higher level of applied pressure, for series 5, can be seen. The additional reduction in life due to selected increases in pressure are also demonstrated, with a 50 to 60 percent decrease in life calculated for the 20 percent increase in applied pressure.
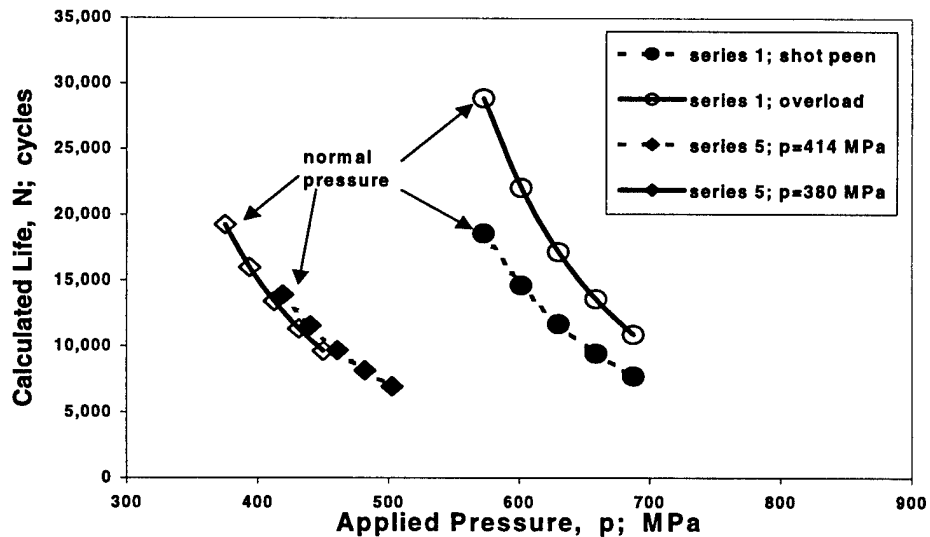

Figure 6. Effect of 5 to 20 percent pressure increase on calculated fatigue lives for various breech conditions.

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SUMMARY AND CONCLUSIONS

A fatigue life model for cannon breech closures has been developed based upon safe fatigue life test results from full-scale cannon breech tests and associated finite element and solid mechanics stress analyses. Key features and results from the model include:

- Close agreement between finite element and solid mechanics calculations of the local concentrated applied stress range at the notch root radius that becomes the fatigue failure site for the cannon breech.

- A 0.94 R^2 correlation of a fracture mechanics-based stress versus fatigue life plot of twenty-eight cannon tests, grouped into six combinations of configuration, material yield strength, and applied and residual stresses.

- Demonstrated high sensitivity of the model to variations in material yield strength, elastic stress concentration factor at the failure site, and residual stress at the failure site.

- Relatively poor agreement with the prior work describing a fatigue life model for cannon tubes, believed due to an inadequate representation of residual stresses in the cannon tube model.

- Demonstration calculations showing significant reductions (up to 60 percent) in breech fatigue life corresponding to relatively small reductions in compressive residual stress or small increases in pressure applied to the cannon breech.

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